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RESEARCH ARTICLE

California Simulation of Evapotranspiration of Applied Water and Agricultural Energy Use in California

Morteza N Orang[1], Richard L Snyder[2], Shu Geng[2, 3], Quinn J Hart[2], Sara Sarreshteh[2], Matthias Falk[2], Dylan Beaudette[2], Scott Hayes[1] and Simon Eching[1]

[1] *California Department of Water Resources, CA 94236-0001, USA*
[2] *Department of Land, Air and Water Resources, University of California, Davis, CA 95616, USA*
[3] *School of Environment and Energy, Shenzhen Graduate School, Peking University, Shenzhen 518055, P.R.China*

Abstract

The California Simulation of Evapotranspiration of Applied Water (Cal-SIMETAW) model is a new tool developed by the California Department of Water Resources and the University of California, Davis to perform daily soil water balance and determine crop evapotranspiration (ET_c), evapotranspiration of applied water (ET_{aw}), and applied water (AW) for use in California water resources planning. ET_{aw} is a seasonal estimate of the water needed to irrigate a crop assuming 100% irrigation efficiency. The model accounts for soils, crop coefficients, rooting depths, seepage, etc. that influence crop water balance. It provides spatial soil and climate information and it uses historical crop and land-use category information to provide seasonal water balance estimates by combinations of detailed analysis unit and county (DAU/County) over California. The result is a large data base of ET_c and ET_{aw} that will be used to update information in the new California Water Plan (CWP). The application uses the daily climate data, i.e., maximum (T_x) and minimum (T_n) temperature and precipitation (P_{cp}), which were derived from monthly USDA-NRCS PRISM data (PRISM Group 2011) and daily US National Climate Data Center (NCDC) climate station data to cover California on a 4 km×4 km change grid spacing. The application uses daily weather data to determine reference evapotranspiration (ET_o), using the Hargreaves-Samani (HS) equation (Hargreaves and Samani 1982, 1985). Because the HS equation is based on temperature only, ET_o from the HS equation were compared with CIMIS ET_o at the same locations using available CIMIS data to determine correction factors to estimate CIMIS ET_o from the HS ET_o to account for spatial climate differences. Cal-SIMETAW also employs near real-time reference evapotranspiration (ET_o) information from Spatial CIMIS, which is a model that combines weather station data and remote sensing to provide a grid of ET_o information. A second database containing the available soil water holding capacity and soil depth information for all of California was also developed from the USDA-NRCS SSURGO database. The Cal-SIMETAW program also has the ability to generate daily weather data from monthly mean values for use in studying climate change scenarios and their possible impacts on water demand in the state. The key objective of this project is to improve the accuracy of water use estimates for the California Water Plan (CWP), which provides a comprehensive report on water supply, demand, and management in California. In this paper, we will discuss the model and how it determines ET_{aw} for use in water resources planning.

Key words: soil water balance, crop water requirements, weather generator, water resource planning, crop coefficient, energy use

INTRODUCTION

The daily soil water balance model California Simulation of Evapotranspiration of Applied Water or Cal-SIMETAW was specifically designed to provide the best possible information on agricultural water demand for use in the California Water Plan, updated every five

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Correspondence Morteza N Orang, Tel: +1-916-6537707, E-mail: morang@water.ca.gov

years to present the status and trends of California's water-dependent natural resources; water supplies; and agricultural, urban, and environmental water demands for a range of plausible future scenarios. California agriculture is a multi-billion dollar industry, number one producer in the nation, and largest consumer of water. The agricultural water demand is high and increasing because water supplies are limited and competition for those supplies is growing. The main factors that are causing increases in agricultural water demand are the population growth and demand for food and fiber. At the same time, the demand for urban and environmental water uses is increasing. The California Department of Water Resources (DWR) and the University of California, Davis (UC Davis) are keenly aware of the need for good planning, and Cal-SIMETAW model was developed to address the planning needs. The Cal-SIMETAW computer application program was written using Microsoft C# for calculations and Oracle Spatial 11g for data storage, as a tool to help DWR obtain accurate estimates of crop evapotranspiration (ET_c), evapotranspiration of applied water (ET_{aw}) for agricultural crops, and urban landscapes, which account for most evapotranspiration losses and water contributions from ground water seepage, precipitation, and irrigation.

Crop evapotranspiration is computed as the product of reference evapotranspiration (ET_o) and a crop coefficient (K_c) value, i.e., $ET_c=ET_o \times K_c$, and ET_{aw}, which is equal to the seasonal evapotranspiration minus water supplied by stored soil moisture, effective rainfall, and seepage from canals. Cal-SIMETAW accounts for contributions from rainfall and for ground water seepage from the rivers and canals when spatial information on the depth to water table is available on the same 4 km×4 km grid spacing used to characterize soils within California.

Cal-SIMETAW has the capability to estimate applied water (AW) by crop and land-use category for each detailed analysis unit and county (DAU/County) combination in the state. Applied water is estimated as the ET_{aw} divided by the mean seasonal irrigation system application efficiency. Thus, the AW supplies estimates of the diversions needed by DWR to plan its future water demand for irrigated agriculture. Seasonal system application efficiency is an estimate of the fraction of AW irrigation water is used to contribute to the crops water requirement. It differs from irrigation efficiency, which includes the crop water requirements, water used for frost protection, and leaching requirements, i.e., beneficial uses, divided by AW over a cropping season.

A major goal of this project was to improve information on current and future water demand. Cal-SIMETAW was developed for water demand planning and it can help to plan for the effects of climate change as well as for current climate conditions. Improvements to the input information and data processing in Cal-SIMETAW greatly enhances our ability to rapidly and accurately determine ET_{aw} for 20 crop categories and 4 land-use categories by each DAU/County within California. All of the ET_{aw} calculations are done on a daily basis, so the estimation of effective seepage of groundwater, effective rainfall and, hence, ET_{aw} is greatly improved over earlier methods. In addition, the use of the widely adopted Penman-Monteith equation for reference evapotranspiration (ET_o) and improved methodology to apply crop coefficients for estimating crop evapotranspiration (ET_c) is used to improve ET_{aw} accuracy for climate change and long-range water resource planning.

Cal-SIMETAW uses batch processing to read (1) the climate data, (2) the surface/crop coefficient values, (3) growth dates to estimate annual curves, (4) soil information, (5) crop and irrigation information, and (6) surface area of each crop and land-use category on each of the 482 DAU/Counties. Then, the program computes daily ET_o, K_c factors, ET_c, daily water balance, effective rainfall, ET_{aw}, etc. for every surface within each of the 482 DAU/Counties over the period of record. The water balance model is similar to that used in the Simulation of ET of Applied Water (SIMETAW) application program, which was also developed as a cooperative effort between the UC Davis and the DWR (Snyder *et al*. 2012). The main difference between the original SIMETAW model and Cal-SIMETAW is that SIMETAW uses historical or generated climate data to determine a daily water balance for individual cropped fields within a watershed region having one set of ET_o estimates, whereas Cal-SIMETAW uses historical or generated climate data and batch files of soil and climate data to compute daily water balance for 20 crop categories, 4 land-use categories over the period of record by DAU/County regions that exhibit a range of evaporative demand and rainfall. Cal-SIMETAW was designed to reduce the time needed for data input and to improve the water use/demand estimates needed for the California Water Plan.

The simulation component of Cal-SIMETAW is useful for studying the effect of climate (e.g., temperature, humidity, CO_2 concentration, and rainfall) change on crop evapotranspiration (ET_c) and evapotranspiration of applied water (ET_{aw}). One of main features of Cal-SIMETAW is that it can simulate daily weather data from monthly climate data, and the simulated data are used to estimate reference ET_o. Because of this feature, Cal-SIMETAW allows the examination of the impact of multiple management scenarios on agricultural water demand using GCM scenarios and regional downsizing models. Using different climate change scenarios from GCM models and a downsizing model to determine means of monthly climate data for 2030 and 2050, Cal-SIMETAW can simulate daily weather data from the monthly mean of solar radiation, maximum and minimum temperature, wind speed, and dew point temperature data to determine ET_o, ET_c, and ET_{aw} for 20 crop categories and 4 land-use categories in each of the 10 hydrologic regions in California. The ability to change the CO_2 concentration was included in Cal-SIMETAW to more accurately estimate the effect of climate change on ET_o in addition to changes in temperature and humidity.

MODEL DESCRIPTION

The Cal-SIMETAW application model was written using Microsoft C# for numerical calculations, graphics, etc. and Oracle software for data storage. In the Cal-SIMETAW project, soil and climate database were developed to spatially characterize ET_c and ET_{aw}. Oracle software was used to store the historical daily climate data, i.e., maximum (T_x) and minimum (T_n) temperatures and precipitation (P_{cp}), which were derived from monthly PRISM data that cover California on a 4 km×4 km grid spacing. Because the PRISM data are monthly and daily data are needed to determine ET_{aw}, daily NCDC climate station data (from October 1921 to September 2010), were used with the PRISM data to estimate daily T_x, T_n, and P_{cp}. The daily climate data development is described later in this paper.

A second database containing the soil water holding capacity and soil depth information was developed from the USDA-NRCS SSURGO database (SSURGO 2011). The developed data base covers all of California on the same 4 km×4 km grid as was used in the SSURGO database.

Using mean soil characteristics and climate and ET_o information from the 4 km×4 km grid, Cal-SIMETAW estimates the mean soil characteristics and ET_o information by DAU/County. The PRISM climate data base (PRISM Group 2011), the Hargreaves-Samani equation, and a calibration factor to convert ET_{HS} to ET_o are used to estimate reference evapotranspiration (ET_o). Crop evapotranspiration is estimated using the single crop coefficient approach (Doorenbos and Pruitt 1977; Allen *et al*. 1998). Up to 20 crop and 4 land-use categories are used to determine weighted crop coefficients to estimate crop evapotranspiration (ET_c) using the single crop coefficient approach (Doorenbos and Pruitt 1977; Allen *et al.* 1998). A daily water balance is computed using input soil and crop information and ET_c. The model can use daily observed climate data or it can generate simulated daily climate data from monthly data to estimate daily ET_o. Information from Spatial CIMIS, which is a model that combines weather station data and remote sensing to provide a grid of ET_o information is also used by Cal-SIMETAW to estimate near real-time ET_o.

Cal-SIMETAW is used by DWR to estimate crop evapotranspiration (ET_c) and evapotranspiration of applied water (ET_{aw}), which is the sum of net irrigation applications needed to produce a crop. Thus, ET_{aw} provides an estimate of the water needed to achieve full evapotranspiration in addition to that water supplied by preseason soil moisture and in-season effective rainfall assuming 100% application efficiency. Dividing the ET_{aw} by the mean seasonal application efficiency (AE) provides an estimate of the seasonal water diversions needed to produce a fully irrigated crop. The application efficiency is the ratio of irrigation water applied that contributes to evapotranspiration to the total applied water.

A first guess for the ET_{aw} would be SET_c, which is the seasonal total ET_c, minus the change in stored soil water during the season and minus any in-season effective rainfall. Therefore, $ET_{aw}=SET_c-SR_e-\Delta SW$, where SR_e is the seasonal effective rainfall and $\Delta SW = SW_i - SW_f$ is change in soil water from the initial soil water content (SW_i) to the final soil water content (SW_f). If the seasonal variables are calculated correctly, the

$\sum NA=SET_c-SR_e-\Delta SW$. The Cal-SIMETAW model uses crop, soil, and climate or weather data to determine the ET_{aw} using the sum of a daily soil water balance. The generated ET_{aw} information provides an estimate of agricultural water demand and thus is important for the California Water Plan.

In addition to using historical data, the weather generator in Cal-SIMETAW can simulate regional daily weather data from monthly climate data that are downscaled from a GCM "General Circulation Model" to estimate ET_o, ET_c, and ET_{aw}. Using crop coefficient data for 20 crop and 4 land-use categories, Cal-SIMETAW estimates daily ET_c, SET_c, and ET_{aw} from 2030 and 2050 climate projections for each of the 10 hydrologic regions within California for use in the California Water Plan.

Purpose of detailed analysis/County units (DAU/County

DWR has subdivided California into 482 DAU/Counties, which are geographic areas having relatively uniform ET_o throughout the region. The regions are used for estimating water demand by agricultural crops and other surfaces for water resources planning. DAUs are based on watershed and other factors related to water transfer and use within the region, which are often split by counties. DAU/Counties are the smallest study areas used by DWR. The largest study areas comprise the ten hydrologic regions. Land use surveys are periodically completed within each DAU/County by DWR staff, and the percentages of each crop within a multiple crop/land-use category are recorded for most DAU/County regions. Using the percentages of each crop within a DAU/County, the individual crop coefficients and growth rates are analyzed to determine a weighted mean K_c curve for each category. Thus, each DAU/county can have as many as 20 crop and 4 land-use categories with weighted mean K_c curves (Fig. 1).

Reference evapotranspiration (ET_o)

Weather and climate data are commonly used to calculate standardized reference evapotranspiration (ET_o) for short canopies (Monteith 1965; Monteith and Unsworth 1990; Allen *et al*. 1998, 2005), but solar radiation, humidity, and wind speed data were lacking from most climate data sets prior to development of CIMIS, i.e., the California Irrigation Management Information System (Snyder and Pruitt 1992). Since only temperature data were available prior to 1986, it was decided to use daily maximum and minimum temperatures and the Hargreaves and Samani (1982, 1985) equation to calculate reference evapotranspiration (ET_{HS}) as an approximation for ET_o. Using recent climate data from CIMIS, comparisons were made between ET_{HS} and ET_o and calibration factors were developed to estimate ET_o from ET_{HS} as a function of wind speed and solar radiation. In general, ET_{HS} was lower than ET_o under windy conditions and it was higher than ET_o under calm conditions. Using approximately 130 CIMIS weather stations distributed across the state, a 4 km×4 km grid of correction factors for the ET_{HS} equation was developed. There are many daily temperature and precipitation weather stations in California, but the PRISM data set (PRISM Group 2011) provided a long-term GIS data base of historical daily maximum and minimum temperature and precipitation on the same 4 km×4 km grid as the correction factor GIS map. Thus, using the PRISM historical temperature data to compute ET_{HS} and the calibration factors, Cal-SIMETAW is able to produce ET_o estimates on a 4 km×4 km grid over the state from October 1921 to September 2010.

ET_o correction factors

National Climate Data Center (NCDC) stations were paired with neighboring CIMIS stations from 1986 through 2010. Corresponding data for the paired stations were selected from the University of California Integrated Pest Management (UC IPM) site (http://ipm.ucdavis.edu). The daily Penman and Monteith equation was used to calculate reference evapotranspiration (ET_o) using daily CIMIS data and the HS equation was used to calculate ET_o (ET_{HS}) using daily T_x and T_n data. The correction factor (C_F) was calculated as: $C_F=ET_o/ET_{HS}$. Spatial interpolation was completed using ARC GIS and a 4 km gridded raster map for CF was produced (Fig. 2). The CF values fell within 15% of 1.0. The CF values were archived for each 4 km×4 km grid area, and the grid areas were stored in files designated by the DAU/County number.

Spatial CIMIS ET_o program

The California Irrigation Management Information System (CIMIS) is a program developed by UC Davis and operated by DWR to help farmers, turf and landscape managers and other resource managers to develop water budgets that improve irrigation scheduling and monitor water stress. CIMIS weather stations are located at key agricultural and municipal sites throughout California to collect comprehensive, timely, weather data on an hourly basis and to disseminate the weather and ET_o data to help farmers and landscape professionals to improve the efficient use of irrigation water. For the Spatial CIMIS program, weather data collection system is combined with NOAA Geostationary Operational Environmental Satellite (GOES) visible satellite data to to extend the reference evapotranspiration (ET_o) estimates to areas not well covered by CIMIS and to provide daily spatial ETo maps. The maps are calculated on a (4 km×4 km) square grid, which is a high spatial resolution when compared to the density of CIMIS stations. The hourly GOES satellite images are used to estimate cloud cover which are used in turn to modify clear sky radiation estimates. These are combined with interpolated CIMIS weather station meteorological data to satisfy the Penman-Monteith ET_o equation (Hart *et al*. 2000).

Real-time Cal-SIMETAW

Cal-SIMETAW provides a method to analyze historical data to determine trends in agricultural water demand, but it is also useful for near real-time demand estimates. Although there are about 130 CIMIS weather stations in California, many locations have limited weather data for ET_o estimation, so there are gaps in the spatial data. To resolve this problem, DWR and UC Davis used satellite data and developed spatial CIMIS to estimate ET_o on a 4 km×4 km grid over the state. Since the Spatial CIMIS uses the same grid as Cal-SIMETAW and it provides near real-time ET_o (i.e., up through the previous day), the output from Spatial CIMIS was incorporated into Cal-SIMETAW and to develop near real-time daily maps of crop ETc. Spatial CIMIS is available and explained on the CIMIS website (CIMIS 2011).

Verification of ET_o data

Results from Cal-SIMETAW were validated against

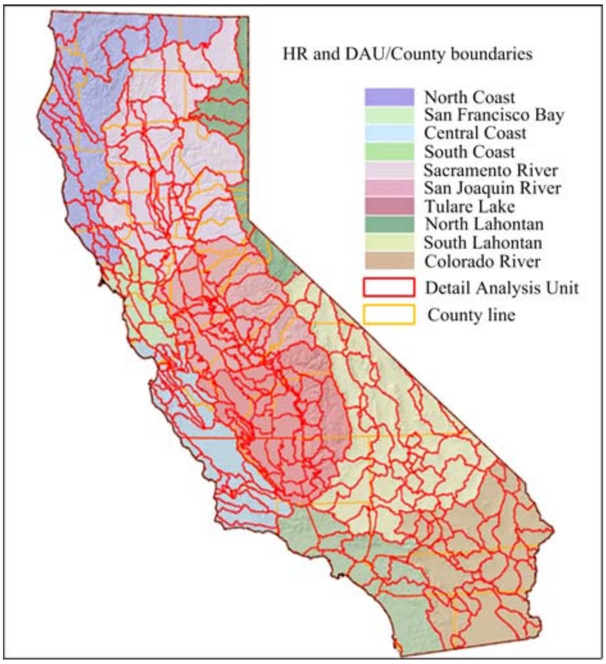

Fig. 1 California study area map showing hydrologic regions, detailed analysis units (DAU), and counties.

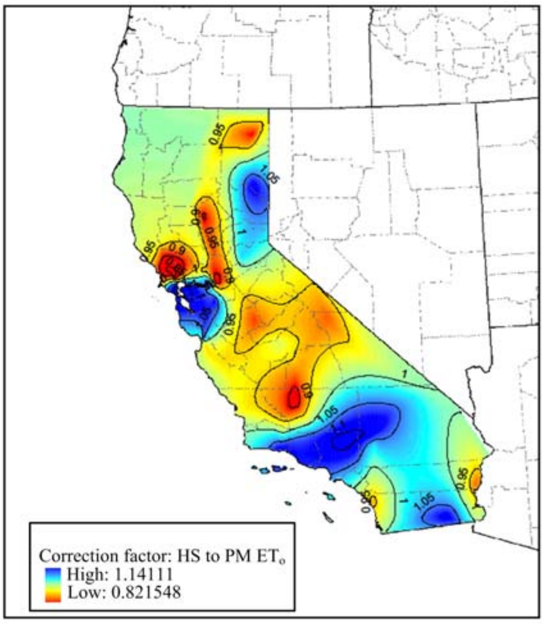

Fig. 2 Correction factor (CF) distribution for converting Hargreaves-Samani ET_o (ETHS) to Penman-Monteith ET_o for California. ET_o=HTHS×CF.

spatial CIMIS ET_o estimates from 2004 to present (Figs. 3-6).

CIMIS network station measurements are among the most reliable direct datasets of daily weather variables including solar radiation (R_s), maximum air temperature (T_m), minimum air temperature (T_n), wind speed (U_2), dew point temperature (T_d), and etc. Reference evapotranspiration (ET_o), computed by the daily (24-h) Penman-Monteith equation, has been recommended by both America Society of Civil Engineers (ASCE) and United Nation FAO. As a final verification of our calibrated Hargreaves-Samani equation for estimating ET_o, a comparison of the calibrated ETHS from Cal-SIMETAW and CIMIS-based estimates of ET_o with data from Davis, California are shown in Figs. 7-9. The results show that estimates of ET_o for 1990-2007 closely approximate ET_o values from CIMIS. The mean ET_o estimates from Davis for the period of 1990-2007 were 3.90 and 3.94 mm with standard deviations of 2.25 and 2.52 mm for the calibrated Hargreaves-Samani model and CIMIS, respectively. The difference between the two approaches was small (roughly 1%).

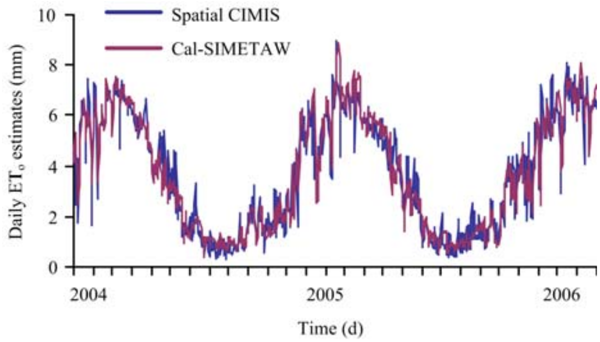

Fig. 3 Comparison of daily ET_o estimates versus time from Cal-SIMETAW and Spatial CIMIS for PRISM grid number 50-60, January 2004-July 2007.

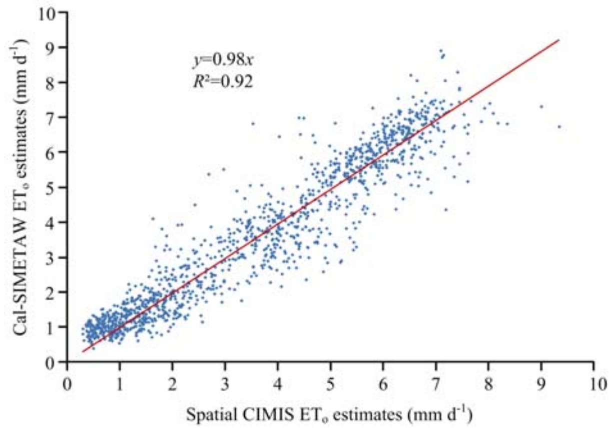

Fig. 4 Comparison between daily ET_o estimates from Cal-SIMETAW versus Spatial CIMIS for PRISM grid number 50-60 from January 2004 through July 2007.

Crop and land-use categories

Daily soil water balance is the key component of the ET_{aw} model. The calculations require input of weather or climate data, soil depth and water-holding capacity, crop root depth, and seasonal crop coefficient curves. Because there are thousands of soil and cropping pattern combinations (including differences in cropping seasons), it is impossible to account for all combination in the state. The biggest limitation is the lack of both historical and current cropping pattern information. In recent years, however, the cropping information has dramatically improved and refinements are likely in the future. To overcome the problem of too many crop and soil combinations, the crops were separated into 20 crop and 4 land-use categories that consist of surfaces with similar characteristics (Table 1).

Soils characteristics and rooting depths

A database containing the soil water holding capacity, soil depth, and rooting depth information for all of California was developed from the USDA-NRCS SSURGO database (SSURGO 2011). The developed database covers all of California on the same 4 km×4 km grid for all locations that are included in the PRISM database, which covers most of California. There are about 26 300 PRISM grids in the model's database for California.

Crop coefficients

Crop evapotranspiration is estimated as the product of reference evapotranspiration (ET_o) and a crop coefficient (K_c) value. Crop coefficients are commonly developed by measuring ET_c, calculating ET_o, and determining the ratio K_c=ET_c/ET_o. Most of the Cal-

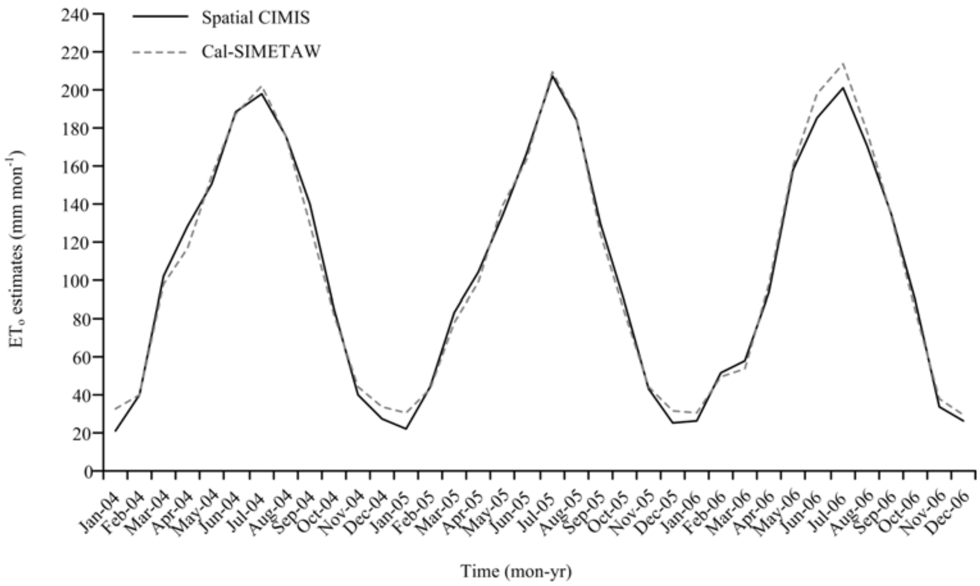

Fig. 5 Comparison of monthly total ET_o estimates versus time for Cal-SIMETAW and Spatial CIMIS for PRISM grid number 50-60, January 2004-December 2006.

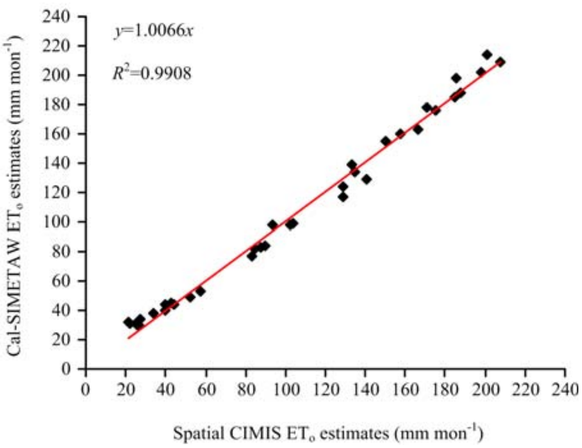

Fig. 6 Comparison between monthly ET_o estimates from Cal-SIMETAW versus Spatial CIMIS for PRSIM grid number 50-60 from January 2004 to December 2006.

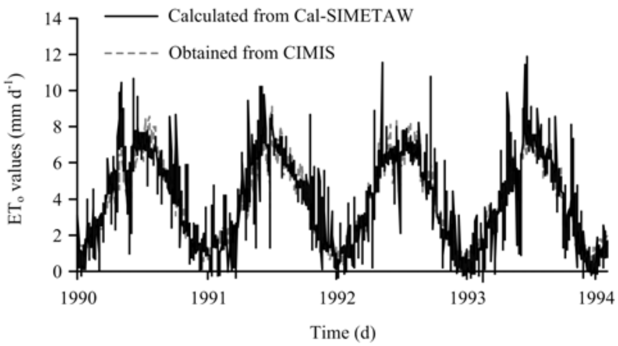

Fig. 7 Comparison of daily ET_o estimates for Cal-SIMETAW and CIMIS at Davis, California within the PRISM grid 99-62 from 1990 to 1994.

SIMETAW crop coefficient values were developed in California, but some were adopted from Doorenbos and Pruitt (1977) and Allen *et al*. (1998). While crop coefficients are continuously developed and evaluated, Cal-SIMETAW was designed for easy updates of both K_c and crop growth information. Also, K_c values need adjustment for microclimates, which are plentiful and extreme in California. A microclimate K_c correction based on the ET_o rate is included in the Cal-SIMETAW model. The K_c values and corresponding growth dates are included by crop in the model. These dates and Kc values are used to estimate daily K_c values during a season.

One of main objectives of this project was to refine and improve crop coefficient values for 20 crop categories on each of the 482 DAU/Counties within the state using the County Ag Commissioner reports (CDFA) and DAU boundaries. Crop categories that represent individual crops have seasonal crop coefficient (K_c) curves, but categories containing multiple crops do not have a single seasonal K_c curve. Using the percentages of each crop within a DAU/County, the crop coefficient and growth data are analyzed to determine a weighted mean K_c curve for each crop category.

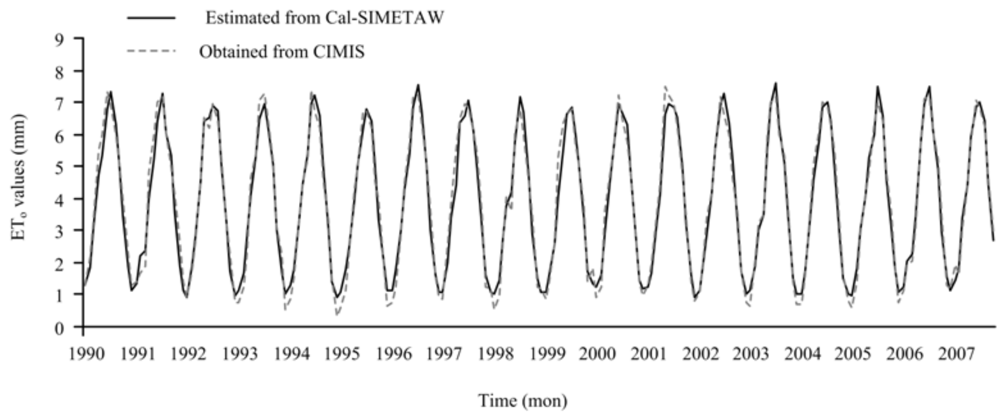

Fig. 8 Comparison of monthly mean ET_o estimates versus time for Cal-SIMETAW and CIMIS at Davis, California within the PRISM grid 99-62 from 1990 to 2007 time period.

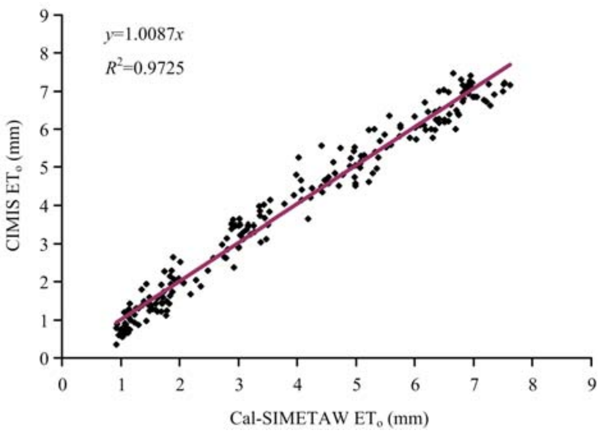

Fig. 9 Comparison of monthly mean ET_o for CIMIS versus Cal-SIMETAW at Davis, California within the PRISM grid 99-62 from 1990 to 2007.

Field and row crops

Field and row crop K_c values are calculated using a method similar to that described by Doorenbos and Pruitt (1977) and Allen *et al*. (1998). A generalized curve is shown in Fig. 10. In their method, the season is separated into initial (date A-B), rapid (date B-C), midseason (date C-D), and late season (date D-E) growth periods. K_c values are denoted K_cA, K_cB, K_cC, K_cD and K_cE at the ends of the A, B, C, D, and E growth dates, respectively. During initial growth, the K_c values are at a constant value, so K_cA=K_cB. During the rapid growth period, when the canopy increases from about 10 to 75% ground cover, the Kc value increases linearly from K_cB to K_cC. The K_c values are typically a constant value during midseason, so K_cC=K_cD. During late-season, the Kc values decrease linearly from K_cD to K_cE at the end of the season (Fig. 10).

Doorenbos and Pruitt (1977) provide estimated number of days for each of the four growth periods to help identify the end dates of growth periods. Because there are climate and varietal differences, however, and because it is difficult for growers to know when the inflection points occur, irrigators often find this confusing. To simplify this problem, percentages of the season from planting to each inflection point rather than days in growth periods are used (Fig. 10). Irrigation planners need only enter the planting and end dates and the intermediate dates are determined from the percentages, which are easily stored in a computer program.

During initial growth of field and row crops, a default K_c=K_cB=K_cA unless it is overridden by entering an initial growth K_c based on rainfall or irrigation frequency.

The values for K_cC=K_cD depend on the difference in (1) light interception, (2) crop morphology effects on turbulence, and (3) physiological differences between the crop and reference crop. Some field crops are harvested before senescence, and there is no late season drop in K_c (for example, silage corn and fresh market tomatoes). Relatively constant annual K_c values are possible for some crops (for example, turfgrass and pasture) with little loss in accuracy.

Table 1 Crop and land-use category numbers, symbols and descriptions

Land-use	Crop symbol	Surface category description
1	GR	Grain (wheat, wheat_winter, wheat_spring, barley, oats, misc._grain & hay)
2	RI	Rice (rice, rice_wild, rice_flooded, rice-upland)
3	CO	Cotton
4	SB	Sugar beet (sugar-beet, sugar_beet_late, sugar_beet_early)
5	CN	Corn
6	DB	Dry beans
7	SA	Safflower
8	FL	Other field crops (flax, hops, grain_sorghum, sudan,castor-beans, misc._field, sunflower, sorghum/sudan_hybrid, millet, sugarcane
9	AL	Alfalfa (alfalfa, alfalfa_mixtures, alfalfa_cut, alfalfa_annual)
10	PA	Pasture (pasture, clover, pasture_mixed, pasture_native, misc._grasses, turf_farm, pasture_bermuda, pasture_rye, klein_grass, pasture_fescue)
11	TP	Tomato processing (tomato_processing, tomato_processing_drip, tomato_processing_sfc)
12	TF	Tomato fresh (tomato_fresh, tomato_fresh_drip, tomato_fresh_sfc)
13	CU	Cucurbits (cucurbits, melons, squash, cucumbers, cucumbers_fresh_market, cucumbers_machine-harvest, watermelon)
14	OG	Onion & garlic (onion & garlic, onions, onions_dry, onions_green, garlic)
15	PO	Potatoes (potatoes, potatoes_sweet)
16	TR	Truck_Crops_misc (artichokes, truck_crops, asparagus, beans_green, carrots, celery, lettuce, peas, spinach, bus h_berries, strawberries, peppers, broccoli, cabbage, cauliflower)
17	AL	Almond & pistacios
18	OR	Orchard (deciduous) (apples, apricots, walnuts, cherries, peaches, nectarines, pears, plums, prunes, figs, kiwis)
19	CS	Citrus & subtropical (grapefruit, lemons, oranges, dates, avocados, olives, jojoba)
20	VI	Vineyards (grape_table, grape_raizin, grape_wine)
21	UR	Urban landscape (cool-season turf, warm-season turf, golf course, open water)
22	RV	Riparian (marsh, tules, sedges, high water table meadow, trees, shrubs, duck marsh)
23	NV	Native vegetation (grassland, light brush, medium brush, heavy brush, forest, oak_woodland)
24	WS	Water surface (river, stream, channel delivery, freshwater_lake, brackish_saline, wastewater)

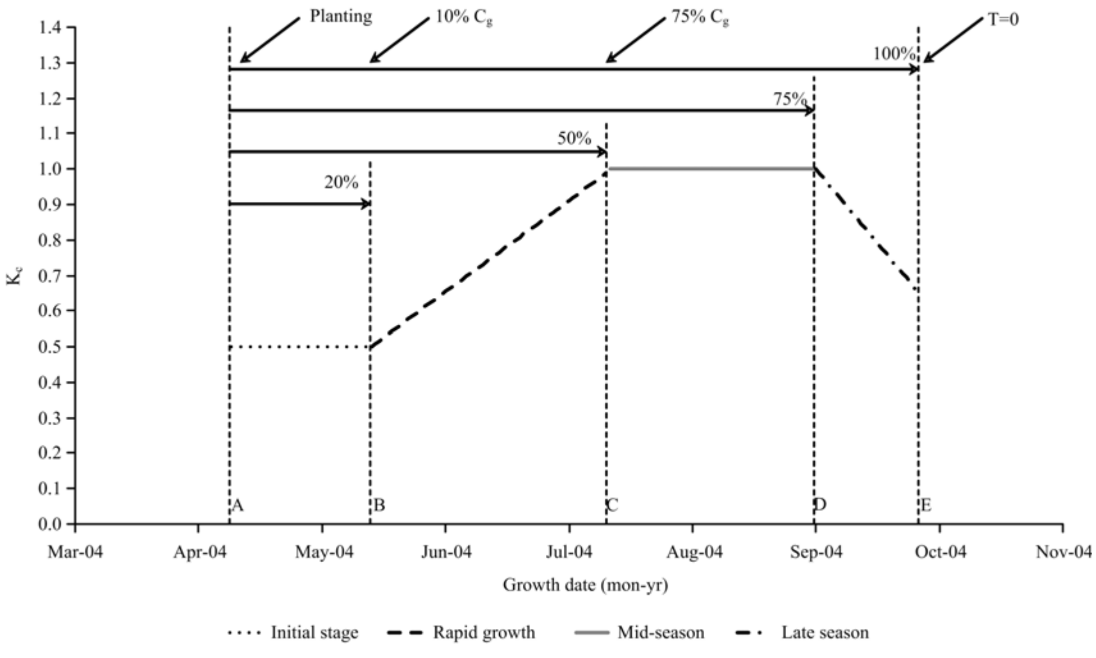

Fig. 10 Hypothetical crop coefficient curve for field and row crops using percentage of the season to delineate growth dates. The season ends when transpiration (T) from the crop ceases (T_0).

Some field crops and landscape plants (type-2 crops) have fixed K_c values all year. However, if the significant rainfall frequency is sufficient to have a higher K_c for bare soil than for the selected crop, then the higher bare soil K_c should be used. The bare soil K_c value serves as a baseline for the crop coefficient, and the higher of the fixed crop K_c or the bare soil K_c is used to estimate ET_c for the crop.

Tree and vine crop K_c values

Deciduous tree and vine crops, without a cover crop, have K_c curves that are similar to field and row crops but without the initial growth period (Fig. 11). Default K_cB, K_cC=K_cD=K_c2 and KcE K_c3 values are included in Cal-SIMETAW. The season begins with rapid growth at leaf out when the Kc increases from K_cB to K_cC. The midseason period begins at approximately 70% ground cover. Then, unless the crop is immature, the K_c is fixed between dates C and D, which corresponds to the onset of senescence. For immature crops, the canopy cover may be less than 70% during the midseason period. If so, the K_c will increase from K_cC up to the K_cD as the canopy cover increases, so the Cal-SIMETAW model accounts for K_c changes of immature tree and vine crops. During late season, the K_c decreases from K_cD to K_cE, which occurs when the transpiration is near zero.

Initially, the K_c value for deciduous trees and vines (K_cB) is selected from a table of default values. However, the ET is mainly soil evaporation at leaf out, so Cal-SIMETAW contains the methodology to determine a corrected K_cB based on the bare soil evaporation. Immature deciduous tree and vine crops use less water than mature crops. The following equation is used to adjust the mature K_c values (K_{cm}) as a function of percentage ground cover (C_g).

$$\text{If } \sin\left[\frac{C_g}{70}\,\frac{\pi}{2}\right] \geqslant 1.0 \text{ then } K_c=K_{cm} \text{ else}$$
$$K_c=K_{cm}\left[\sin\left[\frac{C_g}{70}\,\frac{\pi}{2}\right]\right] \quad (1)$$

Subtropical crops

For mature subtropical orchards (for example, citrus), using a fixed K_c during the season provides acceptable ET_c estimates. If higher on any given date, however, the bare soil K_c replaces the orchard K_c. For an immature orchard, the mature K_c values (K_{cm}) are adjusted for their percentage ground cover (C_g) using the following criteria.

$$\text{If } \sqrt{\sin\left[\frac{C_g}{70}\,\frac{\pi}{2}\right]} \geqslant 1.0 \text{ then } K_c=K_{cm} \text{ or else}$$
$$K_c=K_{cm}\sqrt{\sin\left[\frac{C_g}{70}\,\frac{\pi}{2}\right]} \quad (2)$$

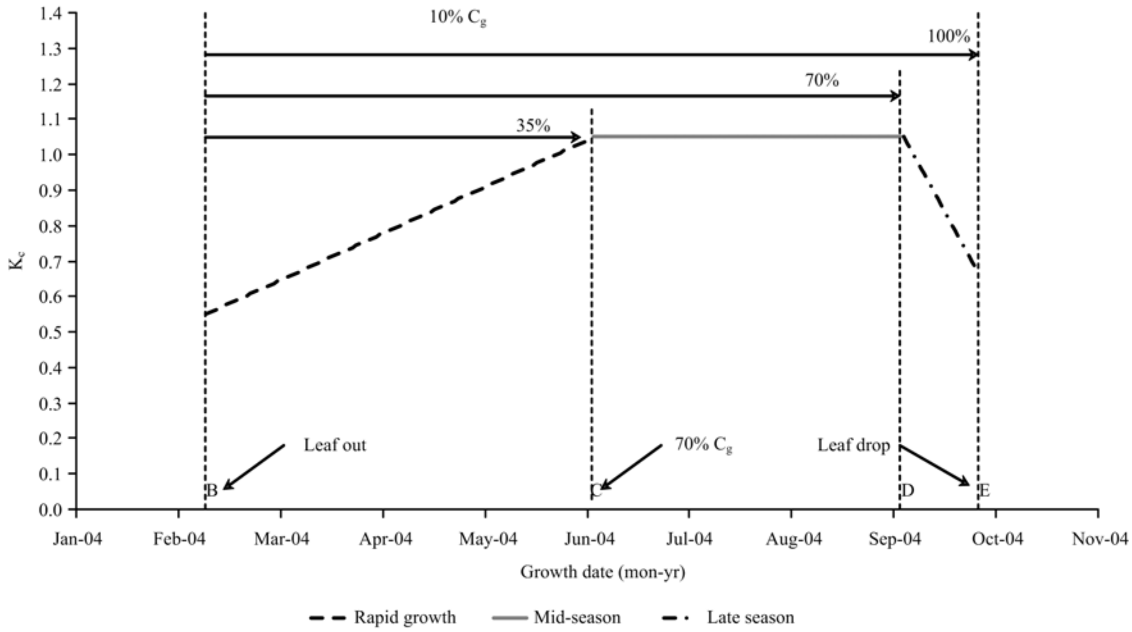

Fig. 11 Hypothetical crop coefficient curve for deciduous tree and vine crops using percentage of the season to delineate growth dates. There is no initial growth period, so the season starts at leaf out on date B.

Cover crop corrections

With a cover crop, the K_c values for orchards and vines are higher. When a cover crop is present, 0.35 is added to the clean-cultivated K_c. However, the K_c is not allowed to exceed 1.20 or to fall below 0.90. Cal-SIMETAW allows the beginning and end dates to be entered for two periods when a cover crop is present in an orchard or vineyard.

Estimating bare soil K_c values

A soil evaporation K_c value, based on ET_o and rainfall frequency is needed as a minimum (base line) for estimating ET_c. It is also useful to determine the K_c value during initial growth of field and row crops ($K_c1=K_cA=K_cB$), based on irrigation frequency, and the starting K_c for deciduous tree and vine crops ($K_c1=K_cB$). The K_c values used to estimate bare soil evaporation are based on a two-stage soil evaporation method reported by Stroonsnjider (1987) and refined by Snyder *et al*. (2000) and Ventura *et al*. (2006). The method provides a K_c values as a function of ETo rate and wetting frequency that are similar to those published in Doorenbos and Pruitt (1977). Computation of the bare soil K_c values is somewhat complicated, so a simplified method was recently developed by comparing the K_c values generated using the model from Ventura *et al*. (2006) with the square root of the cumulative ET_o. The results are shown in Fig. 12. Therefore, a good estimate of a typical bare soil K_c value is obtainable using Fig. 12 shows a bare soil K_c curve as a function of the square root of the cumulative reference evapotranspiration (CET_o).

To determine the baseline Kc from rainfall frequency, the $(CET_o)^{0.5}$ used to determine the bare soil crop coefficient is calculated as:

$$(CET_o)^{0.5}=\sqrt{D_{BR}\times ET_o} \quad (3)$$

Where DBR is the number of days between rainfall events, and ET_o is the mean daily ET_o rate during the non-rainfall period. Then, the bare soil K_c value during that period is estimated as:

$$K_c=\frac{2.54}{\sqrt{CET_o}} \quad (4)$$

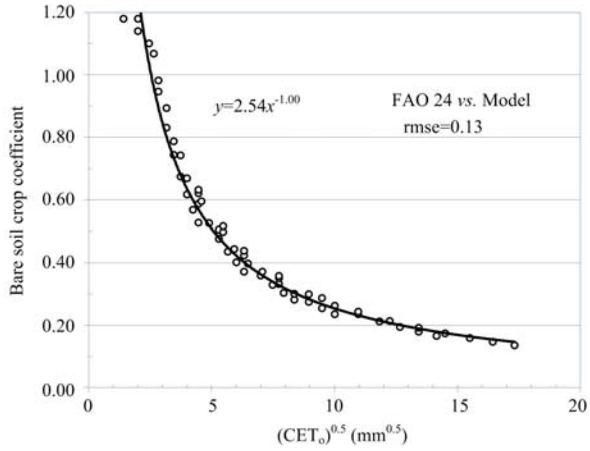

Fig. 12 Bare soil crop coefficient curve as a function of the square root of CET_o.

During the off-season, the bare-soil K_c value is used to estimate the ET. During the season, the bigger of the bare-soil K_c or the K_c based on the crop K_c values is used to calculate the crop evapotranspiration as:

$$ET_c=ET_o\times K_c \quad (5)$$

Fig. 13 presents an example for a tomato crop where the bare-soil K_c (dark line) was higher than the crop K_c (colored line) during part of the season. The green colored line in Fig. 13 shows a K_c curve for a crop that had frequent irrigation after planting that increased the K_c value during initial growth. In all cases, the higher of the bare-soil and crop K_c is used to determine the ET_c on each day.

Evapotranspiration of applied water (ET_{aw})

Irrigation is applied whenever the soil water content on a given day would fall below the management allowable depletion (MAD) set for that date. The net application (NA) amount is the depth of water needed to raise the soil water content back to field capacity (FC) on the irrigation date. The soil water content on each day of the season is calculated as:

$$SWC=SWC_o-D_{sw}+NA \quad (6)$$

Where SWC_o is the soil water content on the previous day, NA is the net application, which is zero on non-irrigation days, and D_{sw} is the daily change in soil water content expressed as:

$$D_{sw}=ET_c-E_{spg}-E_r \quad (7)$$

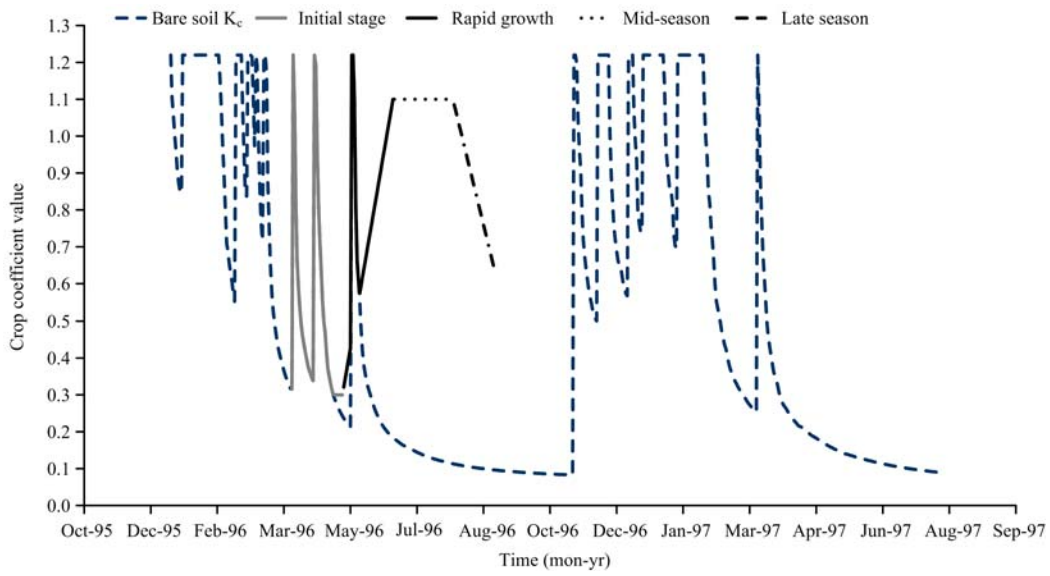

Fig. 13 Daily calculated bare soil and crop coefficient values with different colored lines for each growth period for currently entered daily weather and crop/soil information during the growing season and off-season.

Where ET_c is the evapotranspiration and E_{spg} and E_r are the seepage and effective rainfall contributions to the soil water reservoir.

ET_{aw} is the amount of applied irrigation water that contributes to ET_c; therefore, ET_{aw} is the sum of the net irrigation applications during a cropping season. The ET_{aw} for "n" irrigation events is therefore calculated as:

$$ET_{aw}=NA_1+NA_2+\cdots+NA_n=\sum_{i=1}^{n}NA_i \tag{8}$$

Alternatively, ET_{aw} can be calculated as the seasonal total evapotranspiration (SET_c) minus the cumulative seasonal effective seepage contribution (SE_{spg}) minus the cumulative seasonal effective rainfall contribution (SE_r) minus the difference in soil water content (ΔWC) from the beginning to the end of the season (Fig. 14):

$$ET_{aw}=(SET_c-SE_{spg}-SE_r)-\Delta WC \tag{9}$$

The cumulative seasonal D_{sw} curve (SD_{sw}) is computed as:

$$SD_{sw}=SET_c-SE_{spg}-SE_r \tag{10}$$

Therefore, another expression for ET_{aw} is:

$$ET_{aw}=SD_{sw}-\Delta WC \tag{11}$$

Fig. 14 illustrates how one can determine ET_{aw} from SET_c, SE_{spg}, SE_r, SD_{sw} and ΔSW. Cal-SIMETAW uses the sum of the net applications (eq. (8)) to determine ET_{aw}.

Water balance calculations

Although Cal-SIMETAW has soil characteristic information and computes ET_o on a 4 km×4 km grid, crop planting information is limited to the DAU/County. Therefore, the DAU/County is the smallest unit for calculation of the water balance and thus ET_{aw} for a particular crop or land-use category and soil combination for each DAU/County. Using GIS, a weighted mean value is determined by DAU/County for the soil water holding characteristic, soil depth, root depth, and ET_o. The smaller of the soil and root depth and the weighted

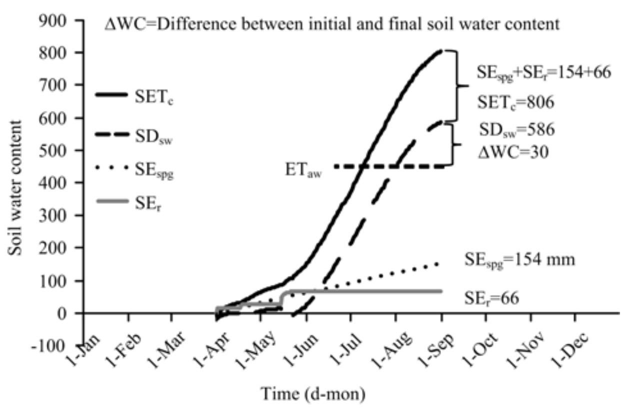

Fig. 14 A plot of SET_c, SE_{spg}, SE_r, and SD_{sw} versus time for a tomato crop to illustrate the calculation of ET_{aw}.

mean water holding characteristics are used to determine the plant available water (PAW). A 50% allowable depletion is used to estimate the readily available water (RAW) for the effective rooting zone. A management allowable depletion (MAD) is determined by comparing the RAW with the cumulative ET_c during the season. The MAD is always less than or equal to RAW, and it is set so that the soil water content at the end of the season is between RAW and PAW.

A crop coefficient curve is determined for each crop or land-use category based on the percentages of individual crop planting areas within that category. The weighted category K_c curves are used with the daily ET_o estimates to calculate daily ET_c for the DAU/County The ET_c is subtracted from the soil water content on each day until the soil water depletion (SWD) exceeds the MAD. Then an irrigation is applied and the soil water depletion goes back to zero (i.e., back to field capacity). Similarly, rainfall will decrease the soil water content to as high as field capacity, but not higher. Rainfall is only effective up to a depth equal to SWD, so effective rainfall cannot exceed the SWD before the rainfall. There is no correction for runoff or runon to the field. It is assumed that rainfall that results in runoff will likely fill the soil to field capacity, and the assumption that effective rainfall cannot exceed SWD still applies. This effective rainfall estimation method works because the water balance calculations are daily. It might fail for for models based on longer than daily water balance calculations. Fig. 15 shows a water balance plot for cotton including the P_{cp}, NA, FC, PWP, SWC, SWC_x, and ET_c, where SWC_x is the water content corresponding to the lower limit of the readily available water.

Verification of water balance calculations

As a final verification of the Cal-SIMETAW model, we also compared our model predictions of annual ET_{aw} for tomato, almond, alfalfa, and avocado crops with an independently derived model called Integrated Water Flow Model (IWFM), which is a water resources management and planning model that simulates groundwater, surface water, stream-groundwater interaction, and other components of the hydrologic system (Dogrul *et al*. 2011). IWFM simulates stream flow, soil moisture accounting in the root zone, flow in the vadose zone, groundwater flow, and stream-aquifer interaction. Agricultural and urban water demands can be pre-specified, or calculated internally based on different land use types (Table 2).

Weather simulation

Weather simulation models are often used in conjunction with other models to evaluate possible crop re-

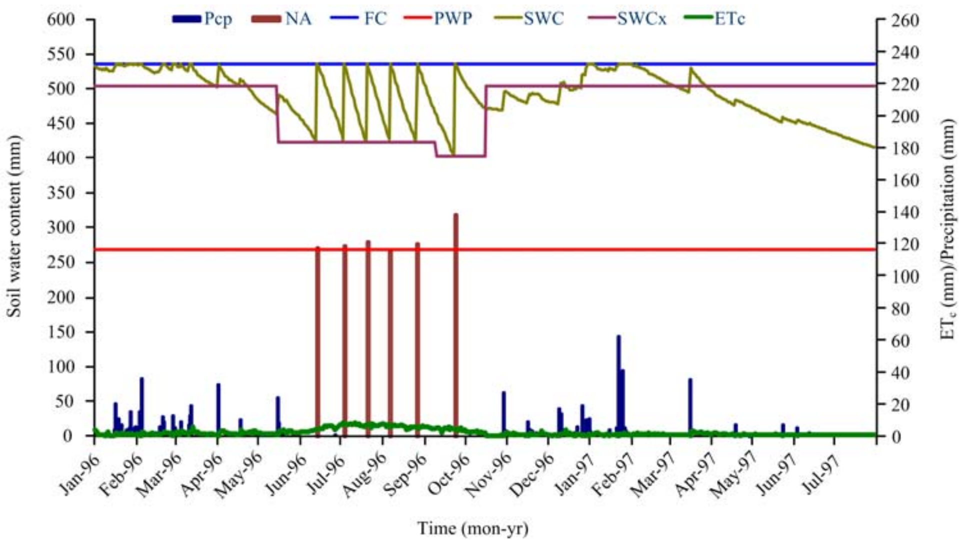

Fig. 15 Fluctuations in soil water content of a cotton crop using a daily water balance.

sponses to environmental conditions. One important response is crop evapotranspiration (ET_c). Crop evapotranspiration is commonly estimated by multiplying reference evapotranspiration by a crop coefficient. In Cal-SIMETAW, climate or projected data are used to estimate daily reference evapotranspiration. Rainfall data are then used with crop and soil information and estimates of ET_c to determine ET_{aw}. One can either use observed or simulated daily data for the calculations.

Rainfall

Characteristics and patterns of rainfall are highly seasonal and localized; it is difficult to create a general, seasonal model that is applicable to all locations. Recognizing the fact that rainfall patterns are usually skewed to the right toward extreme heavy amount and that rain status of the previous day tends to affect the present day condition, a gamma distribution and Markov chain modeling approach was applied to described rainfall patterns for periods within which rainfall patterns are relatively uniform (Gabriel and Neumann 1962; Stern 1980; Larsen and Pense 1982; Richardson and Wright 1984). This approach consists of two models: two-state, first order Markov chain and a gamma distribution function. These models require long-term daily rainfall data to estimate model parameters. Cal-SIMETAW, however, uses monthly averages of total rainfall amount and number of rain days to obtain all parameters for the Gamma and Markov Chain models (Geng *et al*. 1986).

Wind speed

The simulation of wind speed is a simpler procedure, requiring only the gamma distribution function as described for rainfall. Although using a gamma distribution provides good estimates of extreme values of wind speed, there is a tendency to have some unrealistically high wind speed values generated for use in ET_o calculations. Because wind speed depends on atmospheric pressure gradients, no correlation between wind speed and the other weather parameters used to estimate ET_o exists. Therefore, the random matching of high wind speeds with conditions favorable to high evaporation rates leads to unrealistically high ET_o estimates on some days. To eliminate this problem, an upper limit for simulated wind speed was set at twice the mean wind speed. This is believed to be a reasonable upper limit for a weather generator used to estimate ET_o because extreme wind speed values are generally associated with severe storms and ET_o is generally not important during such conditions.

Table 2 A comparison of ET_{aw} calculated with IWFM and Cal-SIMETAW models for tomato, almond, alfalfa, and avocado crops grown in California

Crop	IFWF (mm)	Cal-SIMETAW (mm)
Tomato	697	750
Almond	1 000	1 010
Alfalfa	340	338
Avocado	699	755

Temperature, solar radiation, and humidity

Temperature, solar radiation, and humidity data usually follow a Fourier series distribution. A model of these variables is expressed as:

$$X_{ki}=\mu_{ki}(1+\delta_i C_{ki})_k \quad (12)$$

Where k=1, 2 and 3 (k=1 represents maximum temperature; k=2 represents minimum temperature;and k=3 represents solar radiation), μ_{ki} is the estimated daily mean, and C_{ki} is the estimated daily coefficient of variation of the ith day, i =1, 2, ... , 365 and for the kth variable.

Cal-SIMETAW simplifies the parameter estimation procedure of Richardson and Wright (1984), requiring only monthly means as inputs. From a study of 34 locations within the United States, the coefficient of variability (CV) values appear to be inversely related to the means. The same approach is used to calculate the daily CV values. In addition, a series of functional relationships were developed between the parameters of the mean curves and the parameters of the coefficient of variation curves, which made it possible to calculate C_{ki} coefficients from μ_{ki} curves without additional input data requirement.

Climate change

The ability to make preliminary adjustment for climate change impacts on evapotranspiration and more importantly water balance are included in the Cal-SIMETAW model. The model includes a weather generator that simulates 30 or more years of daily weather data from input monthly means. Statistics from the generated data are nearly identical to observed data. The simulated data are treated like observed data to compute ET_o and estimate ET_c. To study climate change, one only needs to change the monthly mean climate variables to the projected climate. The program adjusts for radiation, temperature, humidity, wind speed, and carbon dioxide concentration. Of course, a bigger effect on irrigated agriculture is the expected change in precipitation. Changing the input monthly precipitation data will modify precipitation patterns, and Cal-SIMETAW will indicate if the demand for irrigation water will change due to the precipitation changes. Thus, Cal-SIMETAW does allow for the input of projected climate change and it will provide information on agricultural water demand in the new scenario. The weather generator in Cal-SIMETAW model allows us to investigate how climate change could affect the water demand in the state. For example, by increasing or decreasing the monthly solar radiation, temperature, and/or dew point temperature, the impact on ET_o, ET_c, and ET_{aw} is easily assessed. The simulation program also allows us to vary CO_2 concentration (ppm) to investigate the effects of increasing CO_2 concentration on ET_o. Since the weather generator in Cal-SIMETAW simulates daily from monthly rainfall data, it also offers the ability to determine the impact of changing rainfall patterns on the water balance and ET_{aw}.

Using monthly mean data from Davis, California, the Cal-SIMETAW simulation model was run using four scenarios: (1) no changes to the current monthly mean data; (2) all monthly maximum and minimum temperatures were increased by 3°C; (3) the same scenario as 2, but also increasing monthly mean dew point temperature by 3°C; (4) the same scenario as 3, but also increasing the CO_2 concentration from 372 to 550 ppm. Relative to scenario 1, the mean daily ET_o rates for an average year increased 18% (scenario 2), 8.5% (scenario 3), and 3.2% (scenario 4). A plot of the mean over 30 years of the simulated scenario data is shown in Fig. 16. This example shows that increases in dew point and CO_2 concentration can at least partially offset increases in ET_o resulting from higher air temperature.

Simulation accuracy

To test the accuracy of Cal-SIMETAW, 29 years of observed daily weather data from the Davis CIMIS station were used in the model to calculate monthly means that were then used to simulate 30 years of daily weather data. The weather data consist of R_s, T_{max}, T_{min}, U_2, T_d, and P_{cp}. The weather data simulated from Cal-SIMETAW were compared with the observed data from CIMIS. Figs. 17-23 illustrate that all Cal-SIMETAW simulated variables and ETo were well correlated with CIMIS observations. The performance of Cal-SIMETAW was also evaluated at using data from Bishop, which is influenced by a windy desert environment on the eastern side of the Sierra Nevada Mountain Range, and with data from Oceanside, which is a coastal site in San Diego County.

Agricultural energy use in California

California agriculture is a multi-billion dollar industry, the number one producer in the nation, and the largest consumer of both water and energy. Most of the energy used by agriculture irrigation goes to pump groundwater. According to the California Energy Commission, California growers use about 20 percent of the total U.S. agricultural electricity, or about 10 000 GWH per year for irrigation. The agricultural energy demand is high and peaking because surface water supplies are limited and pumping groundwater for irrigation is growing. Some of the factors causing for the increases in agricultural energy use, are the intensive use of groundwater storage and drip and micro-sprinkler (drip/micro)

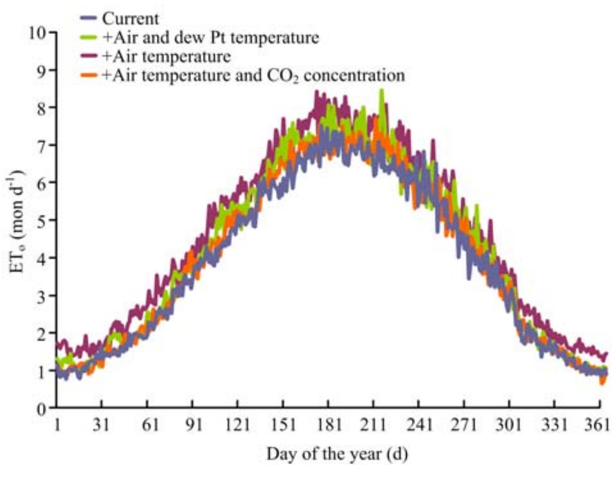

Fig. 16 Comparison of simulated daily ET_o using four different scenarios at Davis, California.

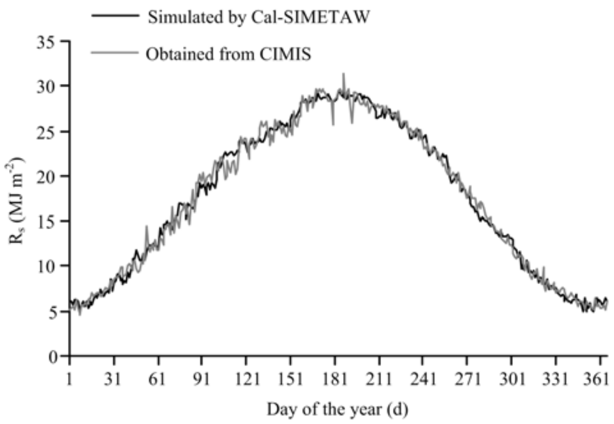

Fig. 17 Comparison of observed and simulated daily solar radiation at Davis, California.

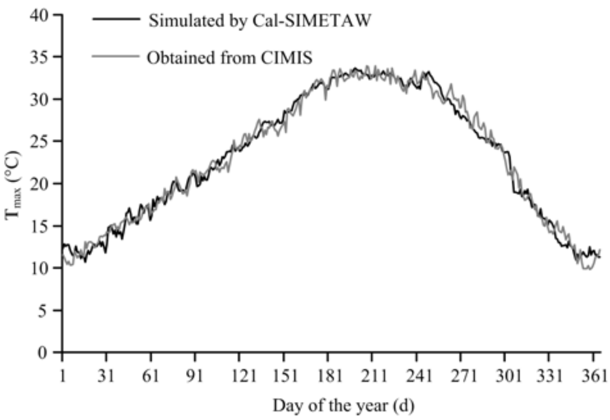

Fig. 18 Comparison of measured and simulated daily maximum air temperature at Davis, California.

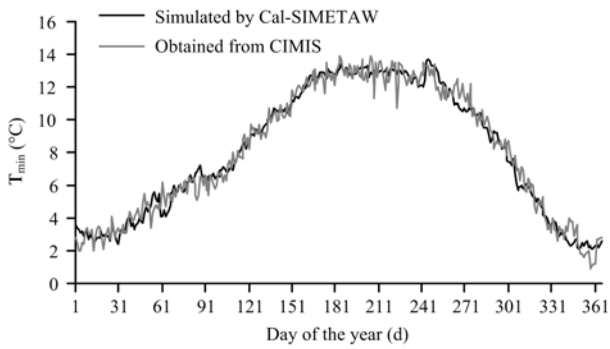

Fig. 19 Comparison of measured and simulated daily minimum air temperature at Davis, California.

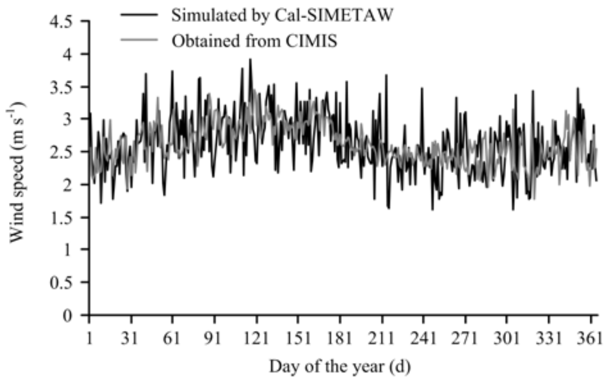

Fig. 20 Comparison of measured and simulated daily wind speed at Davis, California.

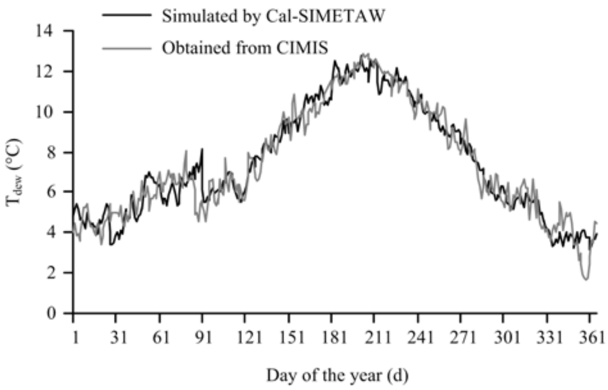

Fig. 21 Comparison of measured and simulated daily dew point temperature at Davis, California.

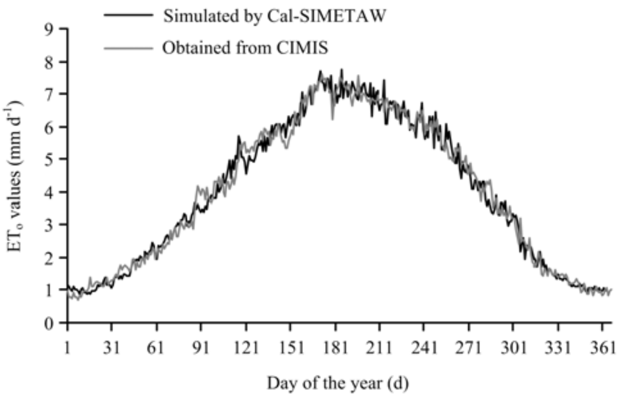

Fig. 22 Comparison of estimated and simulated daily reference evapotranspiration (ET_o) from CIMIS and Cal-SIMETAW at Davis, California .

irrigation systems. The latest statewide irrigation methods survey conducted by DWR and UC Davis during 2011 indicated that drip/micro irrigation systems now cover some 3.2 million acres of irrigated land. Because of changes in crops and management, growers through-

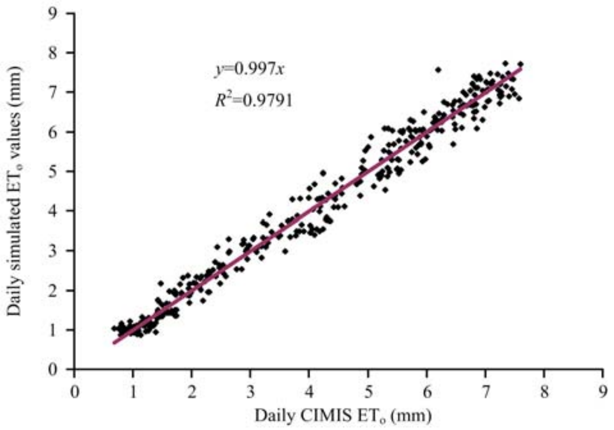

Fig. 23 Cal-SIMETAW estimates of ET_o from simulated climate variables and ET_o from observed climate data from Davis, California CIMIS station.

out the California are now switching to drip/micro irrigation systems to increase production, reduce labor costs, and conserve water. Such systems enable farmers to decrease their need for water, but at the cost of increased energy use. At the same time, farmers are using groundwater storage more intensively than in the past. California State Water Project (SWP), which is maintained and operated by DWR, is also the state's largest user of power. It uses about 40% of its total power consumption to lift the water over the mountains to reach Southern California which lacks adequate local water resources. About 80 percent of the water carried by SWP is used for agriculture in the San Joaquin valley.

Survey of irrigation methods in California

Reliable information on irrigation methods is important for determining agricultural water demand trends. Therefore, DWR and UC Davis conduct a study every 10 years to collect information on irrigation methods that were used by growers to irrigate their crops (Stewart 1975; Snyder *et al*. 1996; Orang *et al*. 2008; Tindula *et al*. 2013). The results are compared to earlier surveys to assess trends in cropping and irrigation method. A one-page questionnaire was developed to collect information on irrigated land by crop and irrigation method. The questionnaire was mailed to 10 000 growers in California that were randomly selected from a list of 58 000 growers by the California Department of Food and Agriculture, excluding rice, dry-land, and livestock producers. From 1972 to 2010, the area planted has increased from 15 to 30% for orchards and from 6 to 15% for vineyards. The area planted to vegetables has remained relatively static, while that planted to field crops has declined from 67 to 41% of the irrigated area. The land irrigated by low-volume (drip and micro-sprinkler) irrigation has increased by about 38%, while the amount of land irrigated by surface methods has decreased by about 37%. Sprinkler usage has decreased in orchards and vineyards, but it increased in vegetable crops. As a result of these trends in irrigation methods, the adoption and usage of ET information for scheduling has increased considerably.

Ways to increase the efficient use of water and energy resources in agriculture

Efficient use of irrigation water and energy is important for maximizing agricultural production and profits per unit of water and energy used. Water and energy use efficiency can be achieved through the use of optimum irrigation water management strategies. An optimum irrigation scheduling, using soil water balance methods minimizes runoff and percolation losses, which in turn maximizes profit and optimizes water and energy use. Other solutions include: (1) reducing non-profit evapotranspiration; (2) improving on farm-irrigation systems and water suppliers systems; (3) using alternative energy sources such as solar and wind power in pumping groundwater for irrigation use; and (4) improving management of surface and groundwater storage to better manage the energy and water associated with water storage.

CONCLUSION

The Cal-SIMETAW model determines effective rainfall and evapotranspiration of applied water (ET_{aw}) for crop and land-use categories, which include similar agricultural crops and other surfaces, by AAU/County regions having similar ET_o rates within California. The model uses daily observed or simulated climate data to account for ET losses and water contributions from seepage of groundwater, rainfall, and irrigation on a daily basis over the period of record to simulate a daily water balance. The model can use daily PRISM climate data or daily climate data simulated from monthly data to estimate daily ET_o. Another feature is that Cal-SIMETAW can employ near real-time ET_o information from Spatial-CIMIS, which is a model that combines weather station data and remote sensing to provide a grid of ET_o information over the state. Cal-SIMEATW computes weighted mean daily crop coefficient factors, crop evapotranspiration, soil water balance, effective seepage of groundwater, and effective rainfall for 20 crop categories and 4 land-use categories within each of the 482 DAU/Counties regions within California. Then, using the surface areas, volumes of water corresponding to crop evapotranspiration and evapotranspiration of applied water are computed for each crop category by DAU/County to provide water deman information that helps the state decide on water supply and distribution needs and solutions. Finally, the weather generator provides the opportunity to investigate possible effects of climate change (e.g., temperature, CO_2 concentration increases, and rainfall patterns) on water demand. This information is extremely important for DWR to develop plans for water supply and distribution across the state.

Acknowledgements

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